

Cosmological Implications of ^3He Destruction on the Red Giant Branch

Arnold I. Boothroyd¹ and Robert A. Malaney

Canadian Institute for Theoretical Astrophysics,

University of Toronto, Toronto, Ontario, CANADA M5S 1A7

Email: boothroy@vulcan.maths.monash.edu.au , malaney@cita.utoronto.ca

ABSTRACT

Observations of stellar CNO isotope ratios indicate the presence of additional mixing processes on the red giant branch. An estimate of the resulting stellar ^3He depletion is made, as a function of stellar mass and metallicity. Based on stellar nucleosynthesis and galactic chemical evolution calculations, we determine the degree to which the destruction of ^3He associated with such extra mixing processes can influence the inferred primordial abundance of $\text{D}+^3\text{He}$. We find that the extra mixing processes may increase the upper limit of the inferred primordial $(\text{D}+^3\text{He})/\text{H}$ ratio by $\sim 20\%$. The implications of this for baryonic dark matter bounds, and constraints on the relativistic degrees of freedom in the early universe, are discussed.

Subject Headings: early universe — Galaxy: abundances — Galaxy: evolution — stars: abundances — stars: AGB and Post-AGB — stars: giants

Preprint CITA-95-27

Submitted to Astrophysical Journal, December 1995

¹ Now at Dept. of Mathematics, Monash University, Clayton, VIC 3168, Australia

1. INTRODUCTION

The upper bound on the inferred primordial abundance of $D+{}^3\text{He}$ plays an important role in cosmology and on the nature of the dark matter. Coupled with calculations of standard big bang nucleosynthesis (SBBN) (see, e.g., Yang *et al.* 1984; Walker *et al.* 1991; Smith *et al.* 1993; Kernan & Krauss 1994; Copi *et al.* 1995a), this bound allows for a lower limit on Ω_b , the baryonic-to-critical density ratio of the universe. Knowledge of the lower limit to Ω_b then allows an upper limit on the relativistic degrees of freedom in the early universe to be set.

Stars burn their initial deuterium to ${}^3\text{He}$ while still on the pre-main sequence. Low mass stars ($1 - 3 M_\odot$) create a ${}^3\text{He}$ -rich pocket in their interior during main sequence burning (Iben 1967; Sackmann & Boothroyd 1995a); this pocket will subsequently be dredged up to the surface on the red giant branch (RGB), and injected into the interstellar medium via stellar mass loss on the RGB and on the asymptotic giant branch (AGB). Thus the sum of $D+{}^3\text{He}$ in the interstellar medium was predicted to increase with time, due to this stellar processing. However, Rood, Bania, & Wilson (1984) pointed out that the apparent observed trend with galactocentric radius of the ${}^3\text{He}$ abundance was the opposite of what one would expect if stellar processing was increasing the galactic ${}^3\text{He}$ abundance. Recent observations of a high ratio $D/H \approx 2.5 \times 10^{-4}$ in a high-redshift quasar absorber (Songaila *et al.* 1994; Carswell *et al.* 1994) has sparked new interest in the subject, since it implied a much larger primordial $(D+{}^3\text{He})/H$ value than had been inferred from the galactic observations (provided that the observed absorption line did indeed correspond to deuterium and not some coincidental interloper cloud happening to lie at the corresponding velocity; note also that in a different line of sight Tytler & Fan [1994] more recently reported a preliminary value as low as $D/H \approx 2 \times 10^{-5}$ in a high-redshift quasar absorber, and that Levshakov & Takahara [1995] have suggested that problems with the turbulent modeling of the absorbing systems could result in very large errors in the derived D abundance.)

The high D/H observation of Songaila *et al.* (1994) and Carswell *et al.* (1994) implied a decline by a factor of order 6 from the primordial $(D+{}^3\text{He})/H$ value to the presolar value. Galli *et al.* (1994, 1995) suggested that a low-energy resonance in the ${}^3\text{He}+{}^3\text{He}$ reaction could increase this rate sufficiently for low mass stars to become net destroyers of ${}^3\text{He}$. Hogan (1995) suggested a less speculative mechanism, namely, *deep extra mixing* below the (relatively cool) base of the conventional convective envelope on the RGB, resulting in nuclear processing of envelope material subsequent to first dredge-up, i.e., “*cool bottom processing*” (CBP). Such extra mixing and resulting CBP is needed in order to understand the puzzle of the low ${}^{12}\text{C}/{}^{13}\text{C}$ ratios observed in low mass Population I RGB stars, and the ${}^{12}\text{C}$ depletion and the $[\text{O}/\text{Fe}] - [\text{Na}/\text{Fe}]$ anticorrelation discovered in low mass Population II RGB stars (see, e.g., Dearborn, Eggleton, & Schramm 1976; Genova & Schatzman 1979; Gilroy 1989; Gilroy & Brown 1991; Dearborn 1992; Smith & Tout 1992; Charbonnel 1994; Boothroyd, Sackmann, & Wasserburg 1995, hereafter BSW95; Wasserburg, Boothroyd, & Sackmann 1995, hereafter WBS95; Denisov & Weiss 1995; Charbonnel 1995). Recently, BSW95 and WBS95 pointed out that such

deep extra mixing should also occur in AGB stars of low mass, in order to account for the anomalously low ^{18}O abundances observed in these stars. (Note that the structure of a star on the AGB is very similar to that of a low-mass star on the RGB; the main difference is that there is a helium-exhausted degenerate core inside the hydrogen-exhausted core. Since the extra mixing and CBP take place outside the core, one would expect them to take place on the AGB as well as on the RGB.) That ^3He can be destroyed in low mass stars raises the serious possibility that the inferred primordial abundance of $\text{D}+^3\text{He}$ could be increased, and consequently the lower bound of Ω_b reduced.

It is the purpose of this report to investigate this interesting possibility in some detail. In section II we present our calculations of the ^3He survival fractions in stars, based on nucleosynthesis models normalized to the observed $^{12}\text{C}/^{13}\text{C}$ and $^{16}\text{O}/^{18}\text{O}$ ratios. Note that WBS95 considered only a $1 M_\odot$ star of solar metallicity; Sackmann & Boothroyd (1995a) used this to make a rough estimate of the average ^3He survival fraction “ g_3 ” for solar metallicity stars. The present work provides improved estimates as a function of both mass and metallicity. In section III we couple these calculations to models of galactic chemical evolution in order to ascertain the highest value of the primordial $\text{D}+^3\text{He}$ abundance consistent with its presolar value. Our basic conclusions will be that additional RGB mixing allows for a consistent picture of $\text{D}+^3\text{He}$ chemical evolution, and that the primordial $\text{D}+^3\text{He}$ abundance remains as the strongest lower bound on Ω_b .

2. STELLAR ^3He PROCESSING

Sackmann & Boothroyd (1995a) present the results of first and second dredge-up (occurring prior to CBP) on the ^3He abundance in stellar envelopes as a function of mass and metallicity, from standard stellar evolution models. In these models, in the absence of any definitive model of ^3He evolution with metallicity, the initial stellar ^3He abundance was chosen by setting $^3\text{He}/Y = 3 \times 10^{-4}$ (abundance mass fraction), where the ^4He mass fraction Y varied according to $Y = 0.24 + 2Z$ with the stellar metallicity Z . Reasonable variations in the initial stellar ^3He abundances would have relatively little effect on the conclusions of this paper.

For CBP models, parametric computations were performed, with envelope structures obtained from models of a solar-metallicity $1 M_\odot$ star (Sackmann, Boothroyd, & Kraemer 1993), not long after first dredge-up on the RGB, and prior to the first He-shell flash (thermal pulse) on the AGB, as discussed in WBS95. In our two-stream “conveyor-belt” circulation model, matter from the bottom of envelope convection streamed downward, reaching a maximum temperature T_P , then returned upward and was mixed with the convective envelope (i.e., a composition advection equation with nuclear burning, and no mixing between downward and upward streams). Envelope and stream compositions were followed through time. The value of T_P was treated as a free parameter; values selected for discussion were those satisfying the observational data, as discussed in WBS95. The results of these $1 M_\odot$ models for ^3He (and other light elements) are presented in Sackmann & Boothroyd (1995a). These models

suggested that low mass stars should deplete ${}^3\text{He}$ (rather than create it), but gave little indication of the ${}^3\text{He}$ depletion expected in stars as a function of mass and metallicity. Note that Charbonnel (1995) has modelled CBP in a low-mass Population II star, using a diffusion algorithm, and also finds a large reduction in the envelope ${}^3\text{He}$ abundance.

Boothroyd & Sackmann (1995) were able to make a rough *relative* estimate of the amount of processing of the CNO isotopes due to CBP, as a function of stellar mass and metallicity. The amount of hydrogen burned on the RGB or AGB is proportional to the advance of the core mass ΔM_c , envelope dilution leads to a factor $(M_{\text{env}})^{-1}$, and variation of the metallicity changes the temperature of CNO burning in the shell, leading to a factor $(Z_{\text{CNO}})^{-1}$, i.e., roughly Z^{-1} . Models of stellar evolution allow one to estimate the value of ΔM_c , and the resulting estimate was presented in Boothroyd & Sackmann (1995).

The nuclear rates for the destruction of ${}^3\text{He}$ are less temperature-sensitive than the CNO-burning rates, and thus a relative estimate of ${}^3\text{He}$ -destruction should have a factor of roughly $Z^{-0.8}$, rather than the above factor of Z^{-1} . Thus the CNO-processing estimate of Boothroyd & Sackmann (1995) was multiplied by $Z^{0.2}$ to get a relative estimate of ${}^3\text{He}$ -destruction due to CBP. This relative estimate was normalized by the $Z = 0.02$, $1 M_\odot$ parametric CBP models. The amount of ${}^3\text{He}$ -destruction in these models was determined on the RGB by the constraint that ${}^{13}\text{C}$ -production must match the observations of ${}^{12}\text{C}/{}^{13}\text{C}$. On the AGB, there are two possible normalizations. One may make the conservative assumption that the normalization should be the same as for the RGB. Alternatively, one may normalize by attempting to match the observed ${}^{18}\text{O}$ -depletion on the AGB (although these observations are less accurate than the RGB carbon isotope observations). The latter normalization results in much more AGB ${}^3\text{He}$ -destruction than the former. The consequences of both alternative normalizations are considered in the present paper.

If CBP is strong enough, the ${}^3\text{He}$ abundance in the stellar envelope may reach an equilibrium value, where ${}^3\text{He}$ destruction is balanced by its creation via the p - p chain. This has been approximated by using information from the parametric models combined with information on the rates of the relevant reactions at the relevant temperatures T_P reached by the extra mixing. For near-solar metallicity, CBP is not strong enough on the RGB to attain the CBP-equilibrium ${}^3\text{He}$ abundance in the available time, and the combined effect of ${}^3\text{He}$ creation and destruction is fairly well constrained by the $1 M_\odot$, $Z = 0.02$ parametric models. On the AGB (or on both RGB and AGB for low metallicity), the temperature T_P is relatively high, and the resulting CBP-equilibrium ${}^3\text{He}$ abundances are quite low (two or more orders of magnitude below the initial stellar ${}^3\text{He}$ abundances); if equilibrium is reached, the remaining amount of ${}^3\text{He}$ is negligible.

Figure 1 presents the predicted ${}^3\text{He}$ enhancement/depletion factors as a function of stellar mass for four different stellar metallicities. The *heavy solid curve* shows the effect of first dredge-up on the RGB (Sackmann & Boothroyd 1995a); as noted above, first dredge-up leads to significant enhancement of the surface ${}^3\text{He}$ abundance in stars with masses below $\sim 4 M_\odot$.

For stars with masses above $\sim 2.3 M_{\odot}$, first dredge-up takes place at the tip of the RGB, and there is no subsequent CBP on the RGB (see Boothroyd & Sackmann 1995). However, in stars of lower mass, the onset of core helium burning is delayed (due to the fact that the helium core is degenerate); these stars have an extended RGB, and experience significant amounts of CBP. The resulting ^3He depletion (at the end of the RGB) is indicated in Figure 1 by the *light solid curves* “1c”; note that they are normalized by the observations of post-first-dredge-up RGB ^{13}C production.

In stars of mass $\sim 4 M_{\odot}$ and above, second dredge-up near the beginning of the AGB causes a slight further depletion of ^3He (Sackmann & Boothroyd 1995a). This is indicated in Figure 1 by the *heavy short-dashed curve*. (Note that where this curve lies above curve “1c” in the $Z = 0.0001$ case, it should be ignored. Above $\sim 7 M_{\odot}$, second dredge-up is interrupted by the ignition of carbon burning in the star’s core; the *dotted curve* shows the ^3He abundance as of the time of core carbon ignition.) The ^{18}O observations do not constrain the time of occurrence of CBP on the AGB; the most conservative assumption is that it occurs throughout the AGB, as long as the hydrogen-shell is burning and there is no composition gradient to oppose it, in analogy to the RGB (see Sackmann & Boothroyd 1995a). A certain amount of CBP is thus expected to occur on the early AGB, during those periods when the hydrogen-shell is burning; the result of this CBP for ^3He is indicated by the *light short-dashed curves* (“2c” and “2o”). Curves “2c” show the effect when the RGB ^{13}C normalization of CBP is used, while curves “2o” show the much stronger depletion that results from using the AGB ^{18}O normalization (these may be regarded as minimum and maximum depletion estimates).

Eventually, periodic helium shell flashes (thermal pulses) begin to take place on the AGB; their onset marks the end of the early AGB and the beginning of the TP-AGB. Stars of roughly $4 - 7 M_{\odot}$ experience hot bottom burning during this stage of evolution, resulting in depletion of ^3He by as much as 6 orders of magnitude (Sackmann & Boothroyd 1992, 1995b). This is shown by the *heavy long-dashed curves* in Figure 1. For stars where hot bottom burning does not take place, CBP is expected to continue during the TP-AGB (interrupted only briefly by the periodic helium shell flashes). The TP-AGB is terminated when mass loss has removed almost all the stellar envelope. For stars of near-solar metallicity, the initial–final mass relationship (Weidemann & Koester 1983; Weidemann 1984) allows one to estimate when this takes place, i.e., to estimate the extent of the TP-AGB and thus the extent of CBP there. For low metallicities, the initial–final mass relationship is sufficiently uncertain that no good estimate can be made. Thus CBP ^3He -depletion on the TP-AGB is estimated only in Figure 1a, as shown by the *light long-dashed curves* “3c” and “3o” (corresponding to the ^{13}C and ^{18}O normalizations, respectively).

Note that ^3He depletion factors for low-metallicity stars are large enough in general that the lack of TP-AGB estimates for these stars is of little importance. Further, the final ^3He estimates of curves “3c” and “3o” may underestimate the *average* ^3He abundance in material returned to the interstellar medium due to mass loss, which occurs throughout the

AGB (though most strongly near the end). For this reason, and for consistency, the curves “2c” and “2o” were used as estimates of the ^3He survival fraction in material returned to the interstellar medium. The curves “2c” in Figure 1 present a conservative estimate of the ^3He survival fraction resulting from dredge-up and CBP; these may be supplemented by the hot bottom burning curves above $\sim 4 M_\odot$, and yield the “low-CBP ^3He -survival” estimate. The much lower ^3He survival fractions of curves “2o” represent an extreme case, the “high-CBP ^3He -survival” estimate. These estimates of the ejected-matter ^3He -survival fraction as a function of stellar mass and metallicity are also tabulated in Table 1.

It should be noted that there is a significant uncertainty in CBP even on the RGB. There is some evidence suggesting that CBP might occur episodically, rather than continuously throughout the relevant period on the RGB (de la Reza *et al.* 1995); processing would then take place at higher temperatures, and the observed amount of ^{13}C -creation might then correspond to a somewhat different amount of ^3He -destruction from that implied by the models of Sackmann & Boothroyd (1995a). Significant star-to-star variations are also possible, and it is possible that some low mass stars experience no CBP at all, as suggested by the high ratio $^3\text{He}/\text{H} \sim 10^{-3}$ (by number) observed in the planetary nebula NGC 3242 by Rood, Bania, & Wilson (1992).

3. CHEMICAL EVOLUTION

Studies regarding the galactic evolution of D and ^3He have a long history, the details of which are described in recent works such as Vangioni-Flam *et al.* (1994), Galli *et al.* 1995, Copi *et al.* (1995b), Scully *et al.* (1995), and Dearborn *et al.* (1995). By lowering the ^3He survival fractions in a parameterized fashion, these works attempt to include in the chemical evolution the effects of ^3He destruction in low mass stars. Here, we wish to couple our *detailed* estimates of ^3He destruction as listed in Table 1, into models of D and ^3He chemical evolution. Our primary goal is to establish the increase in the inferred primordial $(\text{D}+^3\text{He})/\text{H}$ ratio which can reasonably be expected, given that extra mixing processes on the RGB may be occurring. We stress that it is not our role to exhaustively investigate $\text{D}+^3\text{He}$ galactic chemical evolution. Such a study would involve a myriad of possibilities, such as the infall and mixing of the interstellar gas. We merely wish to explore the potential effects of extra RGB mixing on typical chemical evolution models, and to determine if such mixing is an important issue for cosmological constraints. To this end we will adopt the chemical evolution models of Vangioni-Flam *et al.* (1994) as the basis of our study. Vangioni-Flam *et al.* highlight the possible chemical evolution models which can accommodate not only the pre-solar and present D and ^3He data, but also a variety of other constraints such as the metallicity and gas evolution of the galaxy. Use of these models will at least allow us to gauge the importance of our new ^3He survival fractions.

The differential equations describing the evolution of the gas mass fraction σ_g , and the element mass fraction X_i can be written (e.g., Tinsley 1980)

$$\frac{d\sigma_g}{dt} = \int_{m(t)}^{m_{up}} (m - m_r) \Psi(t_m^f) \Phi(m) dm - \Psi(t) \quad , \quad (1a)$$

and

$$\frac{d(\sigma_g X_i)}{dt} = \int_{m(t)}^{m_{up}} m \Psi(t_m^f) \Phi(m) Y_i(t_m^f) dm - X_i \Psi(t) \quad . \quad (1b)$$

Here t_m^f is the formation time at which a star of mass m is returning gas back to the interstellar medium at the current time t . Ψ is the star formation rate (SFR), which we assume to be given by $\Psi = 0.25 \sigma_g$. Y_i is the elemental stellar yield, written as the mass of element i in the ejecta divided by the initial mass of the star from which it was ejected. The lower limit of integration $m(t)$ is the minimum stellar mass which can be returning gas to the interstellar medium at time t . For the remnant mass function m_r , the relations of Iben and Tutukov (1984) are adopted; and for the stellar lifetimes the relations of Scalo (1986) are adopted. For the initial mass function (IMF) $\Phi(m)$, we assume a power law $\Phi(m) \propto m^{-(1+x)}$, normalized through the relation

$$\int_{m_{low}}^{m_{up}} m \Phi(m) dm = 1 \quad . \quad (2)$$

The upper and lower mass limits are taken to be $m_{up} = 100 M_\odot$ and $m_{low} = 0.4 M_\odot$, respectively, and we adopt $x = 1.7$. To this model we couple in the metallicity dependent ^3He survival fractions of Table 1 by adopting a metallicity evolution compatible with presently available data (Edvardsson *et al.* 1993). For more massive stars ($m > 9 M_\odot$) we use a metallicity independent value of $g_3 = 0.25$ (e.g., Dearborn *et al.* 1986), although the results are quite insensitive to this value.

Assuming the low-CBP survival fractions (i.e., minimal ^3He destruction), Figure 2a displays the results of our calculations for various values of the primordial $(\text{D}+^3\text{He})/\text{H}$ ratio. Here we assume a galactic age of 14 Gyr. The data point corresponds to the presolar $(\text{D}+^3\text{He})/\text{H}$ ratio as reported by Geiss (1993), with the error bars indicating the uncertainty at the 2σ level. We assume that the presolar value is representative of the galactic value (local anomalous ^3He values offer another means of achieving compatibility, see for example Olive *et al.* [1995]). That the $(\text{D}+^3\text{He})/\text{H}$ curve pass through this data point is the key test regarding the viability of our initial conditions. In order to satisfy the presolar data we can see from Figure 2a, that the initial value of the $(\text{D}+^3\text{He})/\text{H}$ ratio cannot be greater than 1×10^{-4} . This is essentially the same limit utilized in current studies of SBBN, and resembles the results of model $I_{a,e}$ of Vangioni-Flam *et al.* (1994) who found that an unexplained reduction of g_3 ($g_3 = 0.5, 0.3, 0.3$ for $M = 1, 2, 3 M_\odot$) was necessary for consistency with SBBN.

From the above calculations then, we find that extra mixing on the RGB can indeed lead to lower values of g_3 , but that the extent of this effect only allows for a consistent explanation

of the galactic evolution of ${}^3\text{He}$. More importantly, it does not allow for the lower constraint on Ω_b to be altered.

We have repeated our calculation for the high-CBP survival fractions (i.e., more extreme ${}^3\text{He}$ destruction), the results of which are shown in Figure 2b. It can be seen that these revised survival fractions can influence the results in only in a relatively small way. This is largely a consequence of the fact that even for extremely low g_3 values, $\text{D}+{}^3\text{He}$ cannot be greatly reduced beyond that shown so long as a residual component (say 5%) of the initial gas remains unprocessed. In order to satisfy the presolar data we see from Figure 2b that the initial value of the $(\text{D}+{}^3\text{He})/\text{H}$ ratio cannot be greater than 1.2×10^{-4} .

We have explored numerous variations in our chemical evolution models such as different mass loss rates, SFR laws and IMF's. However, if consistency with all the observable data is to be maintained, the inferred primordial $(\text{D}+{}^3\text{He})/\text{H}$ ratio cannot be increased above $(\text{D}+{}^3\text{He})/\text{H} \approx 1.5 \times 10^{-4}$ (note that this bound is marginally consistent with the value of $\text{D}/\text{H} \approx 2.5 \times 10^{-4}$ observed in a high-redshift quasar absorber by Songaila *et al.* [1994] and Carswell *et al.* [1994]). It is a challenge to model builders to create a reasonable and self-consistent model of galactic chemical evolution which can significantly circumvent this bound.

To put a small change of 0.5×10^{-4} in the upper limit to the inferred primordial $(\text{D}+{}^3\text{He})/\text{H}$ ratio into perspective, we note that it lowers the lower bound on the baryonic density only minimally to $\Omega_b \approx 0.008$, and provides room for additional statistical weight at the epoch of nucleosynthesis of roughly 0.5 equivalent neutrino families. Coupled with the other uncertainties regarding SBBN (e.g., Copi *et al.* 1995a), this would allow for the equivalent of approximately one new neutrino family in the early universe.

4. CONCLUSION

We have investigated in some detail the effect of extra mixing on the RGB as a source of stellar ${}^3\text{He}$ destruction. Through its effects on chemical evolution, we determine the consequences of such ${}^3\text{He}$ destruction for the primordial bound on $\text{D}+{}^3\text{He}$. We find that although a consistent picture of galactic evolution for $\text{D}+{}^3\text{He}$ can emerge, the allowed increase in the primordial $(\text{D}+{}^3\text{He})/\text{H}$ ratio is small, and its impact on the lower limit to Ω_b is minimal. In the extreme ${}^3\text{He}$ -destruction case, a small increase in the relativistic degrees of freedom in the early universe can be accommodated.

We are indebted to I.-J. Sackmann for encouragement and helpful discussions, and wish to thank S. D. Tremaine and P. G. Martin for the support provided by the Canadian Institute for Theoretical Astrophysics. This work was supported in part by a grant from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

- Boothroyd, A. I., & Sackmann, I.-J. 1995, ApJ, submitted; preprint astro-ph/9512121
- Boothroyd, A. I., Sackmann, I.-J., & Wasserburg, G. J. 1995, ApJ, 442, L21 (BSW95)
- Carswell, R. F., Rauch, M., Weymann, R. J., Cooke, A. J., & Webb, J. K. 1994, MNRAS, 268, L1
- Charbonnel, C. 1994, A&A, 282, 811
- . 1995, preprint astro-ph/9511080
- Copi, C. J., Schramm, D. N., & Turner, M. S. 1995a, preprint astro-ph/9508029
- . 1995b, preprint astro-ph/9506094
- Dearborn, D. S. P. 1992, Phys. Reports, 210, 367
- Dearborn, D., Eggleton, P. P., & Schramm, D. N. 1976, ApJ, 203, 455
- Dearborn, D. S. P., Schramm, D. N., & Steigman, G. 1986, ApJ, 302, 35
- Dearborn, D. S. P., Steigman, G., & Tosi, M. 1995, preprint OSU-TA-16/95
- de la Reza, R., Drake, N. A., & da Silva, L. 1995, ApJ (Lett), submitted
- Denissenkov, P. A., & Weiss, A. 1995, A&A, submitted
- Edvardsson, B., Anderson, J., Gustafson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
- Galli, D., Palla, F., Ferrini, F., & Penco, U. 1995, ApJ, 443, 536
- Galli, D., Palla, F., Straniero, O., & Ferrini, F. 1994, ApJ, 432, L101
- Geiss, J. 1993, in *Origin and Distribution of the Elements*, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge; Cambridge University Press), 89
- Genova, F., & Schatzmann, E. 1979, A&A, 78, 323
- Gilroy, K. K. 1989, ApJ, 347, 835
- Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
- Hogan, C. 1995, ApJ, 441, L17
- Iben, I., Jr. 1967, ApJ, 147, 624
- Iben, I., Jr., & Tutukov, A. 1984, ApJS, 54, 335
- Kernan, P., & Krauss, L. 1994, Phys. Rev. Lett., 72, 3309
- Levshakov, S. A., & Takahara, F. 1995, preprint
- Olive, K. A., Rood, R. T., Schramm, D. N., Truran, J. W., & Vangioni-Flam, E. 1995, ApJ, 444, 680
- Rood, R. T., Bania, T. M., & Wilson, T. L. 1984, ApJ, 280, 629
- . 1992, Nature, 355, 618
- Sackmann, I.-J., & Boothroyd, A. I. 1992, ApJ, 392, L71
- . 1995a, ApJ, submitted; preprint astro-ph/9512122
- . 1995b, in preparation
- Sackmann, I.-J., Boothroyd, A. I., & Kraemer, K. E. 1993, ApJ, 418, 457
- Scalo, J. M. 1986, Fund. Cosm. Phys., 11, 1

- Scully, S. T., Cassé, M., Olive, K. A., Schramm, D. N., Truran, J. W., & Vangioni-Flam, E. 1995, preprint astro-ph/9508086
- Smith, G. H., & Tout, C. A. 1992, MNRAS, 256, 449
- Smith, M. S., Kawano, L. H., & Malaney, R. A. 1993, ApJS, 85, 219
- Songaila, A., Cowie, L. L., Hogan, C. J., & Rugers, M. 1994, Nature, 368, 599
- Tinsley, B. M. 1980, Fund. Cosm. Phys., 5, 287
- Tytler, D., & Fan, X. 1994, BAAS, 26, 1424
- Vangioni-Flam, E., Olive, K. A., & Prantzos, N. 1994, ApJ, 427, 618
- Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H. 1991, ApJ, 376, 51
- Wasserburg, G. J., Boothroyd, A. I., & Sackmann, I.-J. 1995, ApJ, 447, L37 (WBS95)
- Weidemann, V. 1984, A&A, 134, L1
- Weidemann, V., & Koester, D. 1983, A&A, 121, 77
- Yang, J., Turner, M. S., Steigman, G., Schramm, D. N., & Olive, K. A. 1994, ApJ, 281, 493

TABLE 1
 ^3He Survival Fractions^a in Ejected Stellar Material From Stars of Mass M

M (M_\odot)	$Z = 0.02$		$Z = 0.007$		$Z = 0.001$		$Z = 0.0001$	
	low-CBP	high-CBP	low-CBP	high-CBP	low-CBP	high-CBP	low-CBP	high-CBP
0.85					0.0246	$1.91(-4)^b$	0.00184	$4.41(-5)$
0.90			0.162	0.00125	0.0291	$1.91(-4)$	0.00268	$4.41(-5)$
0.95			0.185	0.00227	0.0337	$1.91(-4)$	0.00377	$4.41(-5)$
1.00	0.463	0.0124	0.209	0.00409	0.0384	$1.91(-4)$	0.00505	$4.41(-5)$
1.10	0.555	0.0261	0.254	0.0108	0.0486	$1.97(-4)$	0.00789	$4.41(-5)$
1.20	0.626	0.0456	0.304	0.0221	0.0596	$2.73(-4)$	0.0107	$4.41(-5)$
1.35	0.737	0.0691	0.375	0.0371	0.0755	$6.42(-4)$	0.0116	$4.41(-5)$
1.50	0.832	0.0966	0.446	0.0556	0.0936	0.00167	0.0157	$4.41(-5)$
1.65	0.903	0.124	0.513	0.0749	0.115	0.00350	0.0403	$4.41(-5)$
1.80	0.977	0.154	0.596	0.0971	0.144	0.00643	0.195	$4.42(-5)$
2.00	1.106	0.199	0.789	0.134	0.261	0.0138	0.213	$4.43(-5)$
2.25	1.371	0.266	1.650	0.206	1.019	0.0308	0.229	$4.45(-5)$
2.50	1.439	0.302	1.496	0.283	1.007	0.0341	0.245	$4.52(-5)$
2.75	1.310	0.397	1.354	0.326	1.021	0.0423	0.288	$5.29(-5)$
3.00	1.187	0.481	1.235	0.346	1.051	0.0747	0.373	$1.99(-4)$
3.25	1.090	0.512	1.146	0.357	1.110	0.218	0.580	0.00588
3.50	1.014	0.535	1.084	0.411	1.019	0.247	0.1	0.00477
3.75	0.957	0.551	0.316	0.316	0.1	0.1	0.01	0.00790
4.00	0.316	0.316	0.1	0.1	0.01	0.01	0.001	0.001
4.50	0.1	0.1	0.01	0.01	0.001	0.001	$1.(-6)$	$1.(-6)$
5.00	0.01	0.01	0.001	0.001	$1.(-6)$	$1.(-6)$	$1.(-6)$	$1.(-6)$
5.50	0.001	0.001	$1.(-4)$	$1.(-4)$	$1.(-6)$	$1.(-6)$	$1.(-6)$	$1.(-6)$
6.00	0.001	0.001	$1.(-4)$	$1.(-4)$	$1.(-6)$	$1.(-6)$	$1.(-6)$	$1.(-6)$
6.50	0.001	0.001	$1.(-4)$	$1.(-4)$	0.589	0.589	0.505	0.505
7.00	0.001	0.001	0.607	0.607	0.563	0.563	0.477	0.477
7.50	0.568	0.568	0.584	0.584	0.560	0.560	0.495	0.495
8.00	0.547	0.547	0.581	0.581	0.600	0.600	0.501	0.501
8.50	0.522	0.522	0.631	0.631	0.588	0.588	0.484	0.484
9.00	0.538	0.538	0.622	0.622	0.573	0.573	0.471	0.471

^a The ratio of the ^3He abundance (by mass fraction) in ejected material to its initial (input) stellar abundance (by mass fraction) $^3\text{He}_{\text{init}}$; “low-CBP” corresponds to curves “2c” of Fig. 1, and “high-CBP” to curves “2o” of Fig. 1, in both cases supplemented by the effect of hot bottom burning in the relevant mass range.

^b Power of ten notation: $1.91(-4) \equiv 1.91 \times 10^{-4}$.

FIGURE CAPTIONS

Fig. 1.—Log of the ${}^3\text{He}$ survival fraction in the stellar envelope, i.e., the ratio of the ${}^3\text{He}$ abundance (by mass fraction) in the stellar envelope to its initial (input) stellar abundance (by mass fraction) ${}^3\text{He}_{\text{init}}$. Effects of standard dredge-up and (normalized) cool bottom processing estimates are shown, as a function of stellar mass (see text for meaning of curves). (a) For solar ($Z = 0.02$) and near-solar ($Z = 0.007$) metallicity. (b) For low (Population II) metallicities ($Z = 0.001$ and 0.0001).

Fig. 2a.—The galactic evolution of $(\text{D}+{}^3\text{He})/\text{H}$ for low-CBP case, assuming initial values of 12, 10, 9×10^{-5} (top to bottom).

Fig. 2b.—The galactic evolution of $(\text{D}+{}^3\text{He})/\text{H}$ for high-CBP case, assuming initial values of 15, 13, 12, 11, 10×10^{-5} (top to bottom).







